

Cosmological Constant in a Model with Superstring-Inspired E_6 Unification and Shadow θ -Particles

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Abstract

We have developed a concept of parallel existence of the ordinary (O) and mirror (M), or shadow (Sh) worlds. In the first part of the paper we consider a mirror world with broken mirror parity and the breaking $E_6 \rightarrow SU(3)^3$ in both worlds. We show that in this case the evolutions of coupling constants in the O- and M-worlds are not identical, having different parameters for similar evolutions. E_6 unification, inspired by superstring theory, restores the broken mirror parity at the scale $\sim 10^{18}$ GeV. With the aim to explain the tiny cosmological constant, in the second part we consider the breakings: $E_6 \rightarrow SO(10) \times U(1)_Z$ – in the O-world, and $E'_6 \rightarrow SU(6)' \times SU(2)'_\theta$ – in the Sh-world. We assume the existence of shadow θ -particles and the low energy symmetry group $SU(3)'_C \times SU(2)'_L \times SU(2)'_\theta \times U(1)'_Y$ in the shadow world, instead of the Standard Model. The additional non-Abelian $SU(2)'_\theta$ group with massless gauge fields, "thetons", has a macroscopic confinement radius $1/\Lambda'_\theta$. The assumption that $\Lambda'_\theta \approx 2.3 \cdot 10^{-3}$ eV explains the tiny cosmological constant given by recent astrophysical measurements. In this way the present work opens the possibility to specify a grand unification group, such as E_6 , from Cosmology.

*Dedicated to the Memory of Kazuhiko Nishijima,
the founder of the concept of Shadow Universe [1].*

1 Introduction

Modern models for Dark Energy (DE) and Dark Matter (DM) are based on precise measurements in cosmological and astrophysical observations [2–6].

Supernovae observations at redshifts $1.25 \leq z \leq 1.7$ by the Supernovae Legacy Survey (SNLS), cosmic microwave background (CMB), cluster data and baryon acoustic oscillations by the Sloan Digital Sky Survey (SDSS) fit the equation of state for DE: $w = p/\rho$ with constant w , which is given by Ref. [6]:

$$w = -1.023 \pm 0.090 \pm 0.054. \quad (1)$$

The cosmological constant (CC) is given by the vacuum energy density of the Universe [2–6]:

$$CC = \rho_{vac} \approx (3 \times 10^{-3} \text{ eV})^4. \quad (2)$$

The result $w \approx -1$, given by Eq. (1), is consistent with the present model of accelerating Universe [7–11] (see also reviews [12–14]), dominated by a tiny cosmological constant and Cold Dark Matter (CDM) – this is the so-called Λ CDM scenario [15].

The present paper is devoted to the problem of cosmological constant: why it is extremely small. This study develops some ideas considered in Refs. [16–21], but leads to a new interpretation of the possible structure of the Universe having such a tiny CC .

Our model is based on the following assumptions:

- Grand Unified Theory (GUT) is inspired by the superstring theory [22–27], which predicts E_6 unification in the 4-dimensional space [27], occurring at the high energy scale $M_{E_6} \approx 10^{18}$ GeV.
- There exists a Mirror World (MW) [28, 29], which is a duplication of our Ordinary World (OW), or Shadow World (ShW) [1, 30] (hidden sector [31]), which is not identical with the O-world, having different symmetry groups.
- The M-world with broken mirror parity (MP) [32–34], or Shadow world [16–21], describes DE and DM.
- We assume that E_6 unification restores mirror parity at high energies $\approx 10^{18}$ GeV (and at the early stage of the Universe). Then the Mirror World exists and the group of symmetry of the Universe is $E_6 \times E'_6$ (the superscript 'prime' denotes the M-world).

In this paper we consider two models with E_6 unification, one with mirror world and one with shadow world. It is well known (see, for example, Ref. [35]) that there are three schemes of breaking the E_6 group:

$$i) \ E_6 \rightarrow SU(3)_1 \times SU(3)_2 \times SU(3)_3, \quad (3)$$

$$ii) \ E_6 \rightarrow SO(10) \times U(1), \quad (4)$$

$$iii) \ E_6 \rightarrow SU(6) \times SU(2). \quad (5)$$

In the first case, we consider the possibility of the breaking

$$E_6 \rightarrow SU(3)_C \times SU(3)_L \times SU(3)_R$$

in both O- and M-worlds, with broken mirror parity. The model has the merit of an attractive simplicity. We should emphasize that this breaking scheme is the only one which enables us to obtain the E_6 unification of the O- and M- worlds below the Planck scale and with plausible values for the SUSY and seesaw scales. It is quite impossible to obtain the same E_6 unification in the

O- and M-worlds if we have the same breakings *ii*) or *iii*) in both worlds, with broken mirror parity. However, with this model we are unable to explain the tiny CC (2) given by astrophysical measurements, because in this case we have in the low-energy limit the SM in both worlds, which forbids a large confinement radius (i.e. small scale) of any interaction. In the second case, we assume different breakings of the E_6 unification in the O- and Sh-worlds:

$$E_6 \rightarrow SO(10) \times U(1),$$

$$E'_6 \rightarrow SU(6)' \times SU(2)',$$

thus being able to explain the small value of the CC , due to the additional $SU(2)'$ gauge symmetry group appearing at low energies in the Sh-world, which has a large confinement radius. We should point out that there are no other possibilities of breaking the E_6 group, except the breakings (3)-(5).

In the present paper we consider the idea of the existence of theta-particles, developed by Okun [36, 37]¹. In those works it was suggested the hypothesis that in Nature there exists the symmetry group

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times SU(2)_\theta, \quad (6)$$

i.e. with an additional non-Abelian $SU(2)_\theta$ group whose gauge fields are neutral, massless vector particles – thetons. These thetons have a macroscopic confinement radius $1/\Lambda_\theta$. Here we assume that such a group of symmetry exists in the Shadow World at low energy with $\Lambda'_\theta \sim 10^{-3}$ eV and provides the tiny cosmological constant.

2 Superstring theory and E_6 unification

2.1 Superstring theory

Superstring theory [22–27] is a paramount candidate for the unification of all fundamental gauge interactions with gravity. Superstrings are free of gravitational and Yang-Mills anomalies if the gauge group of symmetry is $SO(32)$ or $E_8 \times E_8$.

The 'heterotic' superstring theory $E_8 \times E'_8$ was suggested as a more realistic model for unification [24, 25]. This ten-dimensional Yang-Mills theory can undergo spontaneous compactification. The integration over six compactified dimensions of the E_8 superstring theory leads to the effective theory with the E_6 unification in the four-dimensional space [27]. Among hundreds of papers devoted to the E_6 unification, we would like to single out Refs. [38–45].

2.2 The group E_6

Three 27-plets of E_6 contain three families of quarks and leptons, including right-handed neutrinos N_i^c ($i = 1, 2, 3$ is the index of generations). Matter fields (quarks and leptons) of the fundamental 27-representation of the flipped E_6 decompose under $SU(5) \times U(1)_X$ subgroup as follows:

$$27 \rightarrow (10, 1) + (\bar{5}, -3) + (5, -2) + (\bar{5}, 2) + (1, 5) + (1, 0). \quad (7)$$

¹We are grateful to M. Yu. Khlopov for this information.

The first and second numbers in the brackets of Eq. (7) correspond to the dimensions of the $SU(5)$ representation and to the $U(1)_X$ charges, respectively. The Standard Model (SM) family which contains the doublets of left-handed quarks Q and leptons L , right-handed up and down quarks u^c , d^c , also e^c and right-handed neutrino N^c belongs to the $(10, 1) + (\bar{5}, -3) + (1, 5)$ representations of the flipped $SU(5) \times U(1)_X$. These representations decompose under the groups with the breakings

$$SU(5) \times U(1)_X \rightarrow SU(3)_C \times SU(2)_L \times U(1)_Z \times U(1)_X. \quad (8)$$

Then, for the decomposition (8), we have the following assignments of particles:

$$\begin{aligned} (10, 1) \rightarrow Q &= \begin{pmatrix} u \\ d \end{pmatrix} \sim \left(3, 2, \frac{1}{6}, 1\right), \\ d^c &\sim \left(\bar{3}, 1, -\frac{2}{3}, 1\right), \\ N^c &\sim (1, 1, 1, 1). \end{aligned} \quad (9)$$

$$\begin{aligned} (\bar{5}, -3) \rightarrow u^c &\sim \left(\bar{3}, 1, \frac{1}{3}, -3\right), \\ L &= \begin{pmatrix} e \\ \nu \end{pmatrix} \sim \left(1, 2, -\frac{1}{2}, -3\right), \end{aligned} \quad (10)$$

$$(1, 5) \rightarrow e^c \sim (1, 1, 1, 5). \quad (11)$$

The remaining representations in (8) decompose as follows:

$$\begin{aligned} (5, -2) \rightarrow D &\sim \left(3, 1, -\frac{1}{3}, -2\right), \\ h &= \begin{pmatrix} h^+ \\ h^0 \end{pmatrix} \sim \left(1, 2, \frac{1}{2}, -2\right). \end{aligned} \quad (12)$$

$$\begin{aligned} (\bar{5}, 2) \rightarrow D^c &\sim \left(\bar{3}, 1, \frac{1}{3}, 2\right), \\ h^c &= \begin{pmatrix} h^0 \\ h^- \end{pmatrix} \sim \left(1, 2, -\frac{1}{2}, 2\right). \end{aligned} \quad (13)$$

The light Higgs doublets are accompanied by the heavy coloured Higgs triplets D, D^c which are absent in the SM. The singlet field S is represented by (1,0):

$$(1, 0) \rightarrow S. \quad (14)$$

Let us remark that the flipping of our $SU(5)$,

$$d^c \leftrightarrow u^c, \quad N^c \leftrightarrow e^c, \quad (15)$$

differentiates this group of symmetry from the standard Georgi-Glashow $SU(5)$ [46].

3 E_6 unification in ordinary and mirror world

In this Section we consider the hypothesis that there exists in Nature a mirror world, parallel to our ordinary world [28, 29] (see also Refs. [47–61]). This M-world is a mirror copy of the O-world and contains the same particles and types of interactions as our visible world. The observable elementary particles of our O-world have the left-handed (V-A) weak interactions which violate P-parity. If a hidden mirror M-world exists, then mirror particles participate in the right-handed (V+A) weak interactions and have the opposite chirality.

Lee and Yang were the first [28] to suggest such a duplication of the worlds, which restores the left-right symmetry of Nature. They introduced a concept of right-handed particles, but their R-world was not hidden. The term 'Mirror Matter' was introduced by Kobzarev, Okun and Pomeranchuk [29]. They suggested the 'Mirror World' as the hidden sector of our Universe, which interacts with the ordinary (visible) world only via gravity or another very weak interaction. They have investigated a variety of phenomenological implications of such parallel worlds (for recent comprehensive reviews on mirror particles and mirror matter, see Refs. [62, 63]).

We have assumed that at very high energies $\sim 10^{18}$ GeV, there exists E_6 unification, predicted by superstring theory, in both O- and M-world. In this case, mirror parity (MP) is restored and we have the group of symmetry $E_6 \times E'_6$.

3.1 Particle content in the ordinary and mirror worlds

At low energies we can describe the ordinary and mirror worlds by a minimal symmetry

$$G_{SM} \times G'_{SM},$$

where

$$G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

stands for the Standard Model (SM) of observable particles: three generations of quarks and leptons and the Higgs boson. Then

$$G'_{SM} = SU(3)'_C \times SU(2)'_L \times U(1)'_Y$$

is its mirror gauge counterpart having three generations of mirror quarks and leptons and the mirror Higgs boson. The M-particles are singlets of G_{SM} and the O-particles are singlets of G'_{SM} . *These different O- and M-worlds are coupled only by gravity, or possibly by another very weak interaction.* Including the Higgs bosons Φ , we have the following SM content of the O-world:

$$L - \text{set} : \quad (u, d, e, \nu, \tilde{u}, \tilde{d}, \tilde{e}, \tilde{N})_L, \Phi_u, \Phi_d;$$

$$\tilde{R} - \text{set} : \quad (\tilde{u}, \tilde{d}, \tilde{e}, \tilde{\nu}, u, d, e, N)_R, \tilde{\Phi}_u, \tilde{\Phi}_d;$$

with the antiparticle fields: $\tilde{\Phi}_{u,d} = \Phi_{u,d}^*$, $\tilde{\psi}_R = C\gamma_0\psi_L^*$ and $\tilde{\psi}_L = C\gamma_0\psi_R^*$.

Considering the minimal symmetry $G_{SM} \times G'_{SM}$, we have the following particle content in the M-sector:

$$L' - \text{set} : \quad (u', d', e', \nu', \tilde{u}', \tilde{d}', \tilde{e}', \tilde{N}')_L, \Phi'_u, \Phi'_d;$$

$$\tilde{R}' - \text{set} : \quad (\tilde{u}', \tilde{d}', \tilde{e}', \tilde{\nu}', u', d', e', N')_R, \tilde{\Phi}'_u, \tilde{\Phi}'_d.$$

In general, we can consider a supersymmetric theory when $G \times G'$ contains the grand unification groups $SU(5) \times SU(5)'$, $SO(10) \times SO(10)'$, $E_6 \times E'_6$ etc.

3.2 Mirror world with broken mirror parity

In the general case, mirror parity (MP) is not conserved, and the ordinary and mirror worlds are not identical [32–34, 57–61] in the sense that, although the chain of breakings of the gauge groups is the same in both worlds, the energy scales at which these breakings take place are different.

If the O- and M-sectors are described by the minimal symmetry group

$$G_{SM} \times G'_{SM}$$

with the Higgs doublets Φ and Φ' , respectively, then in the case of non-conserved MP the VEVs of Φ and Φ' are not equal: $v \neq v'$. In accord with Refs. [32–34, 57–61], we assume that

$$v' \gg v$$

and introduce the parameter characterizing the violation of MP:

$$\zeta = \frac{v'}{v} \gg 1. \quad (16)$$

Then the masses of fermions and massive bosons in the mirror world are scaled up by the factor ζ with respect to the masses of their counterparts in the ordinary world:

$$m'_{q',l'} = \zeta m_{q,l}, \quad (17)$$

$$M'_{W',Z',\Phi'} = \zeta M_{W,Z,\Phi}, \quad (18)$$

while photons and gluons remain massless in both worlds.

Let us consider now the expressions for the running of the inverse coupling constants,

$$\alpha_i^{-1}(\mu) = \frac{b_i}{2\pi} \ln \frac{\mu}{\Lambda_i}, \quad \text{in the O-world;} \quad (19)$$

$$\alpha'^{-1}_i(\mu) = \frac{b'_i}{2\pi} \ln \frac{\mu}{\Lambda'_i}, \quad \text{in the M-world.} \quad (20)$$

Here $i = 1, 2, 3$ correspond to $U(1)$, $SU(2)$ and $SU(3)$ groups of the SM (or SM'). A big difference between the electroweak scales v and v' will not cause the same difference between the scales Λ_i and Λ'_i . Hence,

$$\Lambda'_i = \xi \Lambda_i. \quad (21)$$

The value of ζ was estimated by astrophysical implications [32–34] which led to

$$\zeta \approx 30. \quad (22)$$

In general, ζ can be considered in the range 10-100.

3.3 Seesaw scale in the ordinary and mirror worlds

In the language of neutrino physics, the O-neutrinos ν_e, ν_μ, ν_τ are active neutrinos, while the M-neutrinos $\nu'_e, \nu'_\mu, \nu'_\tau$ are sterile neutrinos. The model [32–34, 57–61] provides a simple explanation of why sterile neutrinos could be light, and could have significant mixing with the active neutrinos.

If MP is conserved ($\zeta = 1$), then the neutrinos of the two sectors are strongly mixed. But it seems that the situation with the present experimental and cosmological limits on the active-sterile neutrino mixing do not confirm this result. If instead MP is spontaneously broken, and $\zeta \gg 1$, then the active-sterile mixing angles should be small:

$$\theta_{\nu\nu'} \sim \frac{1}{\zeta}. \quad (23)$$

As a result, we have the following relation between the masses of the light left-handed neutrinos:

$$m'_\nu \approx \zeta^2 m_\nu. \quad (24)$$

In the context of the SM, in addition to the fermions with non-zero gauge charges, one introduces also the gauge singlets, the so-called right-handed neutrinos N_a with large Majorana mass terms. According to Refs. [32–34, 57–61], they have equal masses in the O- and M-worlds:

$$M'_{\nu,a} = M_{\nu,a}. \quad (25)$$

Let us consider now the usual seesaw mechanism. Heavy right-handed neutrinos are created at the seesaw scales M_R in the O-world and M'_R in the M- or Sh-world. From the Lagrangian, considering the Yukawa couplings identical in the two sectors, it follows that

$$m_\nu^{(\prime)} = \frac{v^{(\prime)2}}{M_R^{(\prime)}}, \quad (26)$$

and we immediately obtain the relations (24), with

$$M'_R = M_R. \quad (27)$$

Then we see that even in the model with broken mirror parity, we have the same seesaw scales in the O- and M- or Sh-worlds.

4 Model with breaking $E_6 \rightarrow SU(3)_C \times SU(3)_L \times SU(3)_R$ in ordinary and mirror worlds

We assume that in the ordinary and mirror worlds there exists the symmetry

$$G \times G'.$$

In the ordinary world, from the SM up to the E_6 unification, G represents the following chain of restoration of symmetry groups:

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

$$\begin{aligned}
& \rightarrow [SU(3)_C \times SU(2)_L \times U(1)_Y]_{SUSY} \\
& \rightarrow SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X \times U(1)_Z \\
& \rightarrow SU(3)_C \times SU(3)_L \times SU(2)_R \times U(1)_Z \\
& \rightarrow SU(3)_C \times SU(3)_L \times SU(3)_R \rightarrow E_6,
\end{aligned} \tag{28}$$

and in the mirror world G' represents the symmetry group chain of the same structure:

$$\begin{aligned}
& SU(3)'_C \times SU(2)'_L \times U(1)'_Y \\
& \rightarrow [SU(3)'_C \times SU(2)'_L \times U(1)'_Y]_{SUSY} \\
& \rightarrow SU(3)'_C \times SU(2)'_L \times SU(2)'_R \times U(1)'_X \times U(1)'_Z \\
& \rightarrow SU(3)'_C \times SU(3)'_L \times SU(2)'_R \times U(1)'_Z \\
& \rightarrow SU(3)'_C \times SU(3)'_L \times SU(3)'_R \rightarrow E'_6.
\end{aligned} \tag{29}$$

Also we have assumed that the E_6 unification, being the same in the O- and M-worlds ($E_6 = E'_6$, which means the same unification scales, $M_{E_6} = M'_{E_6}$, with the same super-super-GUT² coupling constants, $g_{E_6} = g'_{E_6}$), restores the broken mirror parity MP at the super-super-GUT-scale $M_{E_6} \sim 10^{18}$ GeV. At low energies we have the Standard Model in both worlds, $G_{SM} \times G'_{SM}$, for which case the mirror world with broken mirror parity has been studied in Refs. [32–34, 57–61].

4.1 Gauge coupling constant evolutions in the O- and M-worlds

In this work we consider the running of all the gauge coupling constants in the SM and its extensions which is well described by the one-loop approximation of the renormalization group equations (RGEs), since from the Electroweak (EW) scale up to the Planck scale (M_{Pl}) all the non-Abelian gauge theories with rank $r \geq 2$ appearing in our model are chosen to be asymptotically free. With this aim we consider only the Higgs bosons belonging to the $N + \bar{N}$ representations for $SO(N)$ or $SU(N)$ symmetry breaking [44].

For the energy scale $\mu \geq M_{ren}$, where M_{ren} is the renormalization scale, we have the following evolution for the inverse coupling constants α_i^{-1} given by RGE in the one-loop approximation:

$$\alpha_i^{-1}(\mu) = \alpha_i^{-1}(M_{ren}) + \frac{b_i}{2\pi}t, \tag{30}$$

where

$$\alpha_i = \frac{g_i^2}{4\pi}$$

and g_i is the gauge coupling constant of the gauge group G_i . Here

$$t = \ln \left(\frac{\mu}{M_{ren}} \right).$$

The coefficients (slopes) b_i , describing the running of the coupling constants with our choice of gauge groups and particle content, are given in Table 1 (according to Refs. [20, 44, 64, 65]), for both O- and M-worlds.

²The prefix "super" refers to higher unification scales, in the order GUT, super-GUT, super-super-GUT etc.

NonSUSY groups: b_i :	$SU(3)_C$ 7	$SU(2)_L$ 19/6	$U(1)_Y$ -41/10	
SUSY groups: b_i^{SUSY} :	$SU(3)_C$ 3	$SU(2)_{L,R}$ -1	$SU(2)_L \times SU(2)_R$ $b_{22} = -2$	$U(1)_Y$ -33/5
	$SU(3)_C \times SU(3)_L$ $b_{33} = 9$	$U(1)_X$ -33/5	$U(1)_Z$ -33/5	$SU(3)_C \times SU(3)_L \times SU(3)_R$ $b_{333} = 21$

Table 1: The coefficients b_i in the O- and M-worlds.

In the following, we shall use the fact that the running of the coupling constants is the same in the O- and M-world, since the gauge groups of symmetry and the particle content are the same in the two worlds, but the scales of the gauge symmetry breakings are different, due to the violation of mirror parity.

In our model we shall consider

$$\zeta = 10. \quad (31)$$

4.2 Standard Model

We start with the SM in the ordinary world:

$$G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

and SM' in the mirror world:

$$G'_{SM'} = SU(3)'_C \times SU(2)'_L \times U(1)'_Y.$$

For compactness of notation, in the following we shall denote by $\alpha^{(\prime)-1}$ the inverse of various coupling constants and by $M_{ren}^{(\prime)}$ the various renormalization scales belonging to either ordinary world (the non-primed symbols) or mirror world (the primed symbols). For energy scales $\mu \geq M_t$ (M_t – top quark mass) in the SM and $\mu \geq M'_t$ ($M'_t = \zeta M_t$ – mirror top quark mass) in the SM' we have the following evolutions (RGEs) [64–66] for the inverse coupling constants $\alpha_i^{(\prime)-1}$ ($i = 1, 2, 3$ correspond to the $U(1)^{(\prime)}$, $SU(2)^{(\prime)}$ and $SU(3)^{(\prime)}$ groups of the $SM^{(\prime)}$, respectively):

$$\alpha_1^{(\prime)-1}(t) = \alpha_1^{(\prime)-1}(M_t^{(\prime)}) - \frac{41}{20\pi}t^{(\prime)}, \quad (32)$$

$$\alpha_2^{(\prime)-1}(t) = \alpha_2^{(\prime)-1}(M_t^{(\prime)}) + \frac{19}{12\pi}t^{(\prime)}, \quad (33)$$

$$\alpha_3^{(\prime)-1}(t) = \alpha_3^{(\prime)-1}(M_t^{(\prime)}) + \frac{7}{2\pi}t^{(\prime)}, \quad (34)$$

where

$$\alpha_1^{-1}(M_t) = \alpha_1'^{-1}(M'_t) = 58.65 \pm 0.02, \quad (35)$$

$$\alpha_2^{-1}(M_t) = \alpha_2'^{-1}(M'_t) = 29.95 \pm 0.02, \quad (36)$$

$$\alpha_3^{-1}(M_t) = \alpha_3'^{-1}(M'_t) = 9.17 \pm 0.20, \quad (37)$$

and the evolution variables are

$$t = \ln \left(\frac{\mu}{M_t} \right) \quad \text{and} \quad t' = \ln \left(\frac{\mu}{M'_t} \right).$$

We have used the central value of the top quark mass (Particle Data Group [67]):

$$M_t = 172.6 \text{ GeV},$$

implying, for $\zeta = 10$, $M'_t = 1.726 \text{ TeV}$.

In Eq. (37) the value of $\alpha_3^{-1}(M_t) = 9.17$ essentially depends on the value of

$$\alpha_3(M_Z) \equiv \alpha_s(M_Z) = 0.118 \pm 0.002$$

(see Particle Data Group [67]), where M_Z is the mass of the Z -boson. The value of $\alpha_3^{-1}(M_t)$ is given by the running of $\alpha_3^{-1}(\mu)$ from M_Z up to M_t , via the Higgs boson mass M_H . Here we have used $M_H = 130 \pm 15 \text{ GeV}$, in accord with the observed experimental data at LEP2 and Tevatron.

If we assume now that for $\mu \leq M_t$ in the O-world:

$$\alpha_2^{-1}(\mu) = \frac{b_2}{2\pi} \ln \frac{\mu}{\Lambda_2}, \quad (38)$$

and for $\mu \leq M'_t$ in the M-world:

$$\alpha'^{-1}_2(\mu) = \frac{b_2}{2\pi} \ln \frac{\mu}{\Lambda'_2}, \quad (39)$$

with

$$\Lambda'_2 < \Lambda_2 \quad (\xi < 1 \text{ in (21)}), \quad (40)$$

then we know that $\alpha_2^{(\prime)-1}(\mu)$ runs down to low energies, but stops at some scale with coupling constant $g_2^{(\prime)}$ corresponding to the Fermi constant G_F of the 4-fermion weak interaction. This is a consequence of the existence of the Higgs particles. As it was shown in Subsection 3.2, the SM VEVs of the Higgs fields are: $\langle \Phi \rangle = v = 246 \text{ GeV}$ and $\langle \Phi' \rangle = v' = \zeta v$. Then the intermediate bosons $W(W')$ and $Z(Z')$ acquire the masses $M_{W,Z}$ known in the SM and $M'_{W',Z'}$ given by Eq. (18). As a result, an extremely large confinement radius is absent. But if the intermediate bosons would not acquire mass due to the Higgs mechanism, then their gauge interaction would be characterized by a macroscopic radius of confinement. In this case we could have a scale Λ_2 or Λ'_2 at extremely low energies. However, we do not have such an extremely small scale in the Standard Model.

4.3 MSSM

The Minimal Supersymmetric Standard Model (MSSM^(\prime)) (which extends the conventional SM^(\prime)) gives the evolutions for $\alpha_i^{(\prime)-1}(\mu)$ ($i = 1, 2, 3$ correspond to the $U(1)^{(\prime)}$, $SU(2)^{(\prime)}$, $SU(3)^{(\prime)}$ groups, respectively) from the supersymmetric scale $M_{SUSY}^{(\prime)}$ up to the seesaw scale $M_R^{(\prime)}$, where the heavy (mirror) right-handed neutrinos are produced. In MSSM' the superpartners of particles, i.e., "sparticles", have in the M-world the masses $\tilde{m}' = \zeta \tilde{m}$. This means that the supersymmetry breaking scale in the M-world is larger:

$$M'_{SUSY} = \zeta M_{SUSY}.$$

At the seesaw scale $M'_R = M_R$, the mirror right-handed neutrinos appear.

From (32)-(34), one easily obtains:

$$\alpha_1^{-1}(M_{SUSY}) = \alpha_1'^{-1}(M'_{SUSY}) = 56.01, \quad (41)$$

$$\alpha_2^{-1}(M_{SUSY}) = \alpha_2'^{-1}(M'_{SUSY}) = 31.99, \quad (42)$$

$$\alpha_3^{-1}(M_{SUSY}) = \alpha_3'^{-1}(M'_{SUSY}) = 13.68, \quad (43)$$

for $M_{SUSY} = 10$ TeV and $M'_{SUSY} = \zeta M_{SUSY} = 100$ TeV, when $\zeta = 10$. Above these scales we have, according to Table 1:

$$\alpha_1^{(\prime)-1}(t_s^{(\prime)}) = \alpha_1^{(\prime)-1}(M_{SUSY}^{(\prime)}) - \frac{33}{10\pi} t_s^{(\prime)}, \quad (44)$$

$$\alpha_2^{(\prime)-1}(t_s^{(\prime)}) = \alpha_2^{(\prime)-1}(M_{SUSY}^{(\prime)}) - \frac{1}{2\pi} t_s^{(\prime)}, \quad (45)$$

$$\alpha_3^{(\prime)-1}(t_s^{(\prime)}) = \alpha_3^{(\prime)-1}(M_{SUSY}^{(\prime)}) + \frac{3}{2\pi} t_s^{(\prime)}, \quad (46)$$

with the respective evolution parameters in the O- and M-worlds:

$$t_s = \ln \left(\frac{\mu}{M_{SUSY}} \right) \quad \text{and} \quad t'_s = \ln \left(\frac{\mu}{M'_{SUSY}} \right).$$

4.4 Left-right symmetry

We assume that the following supersymmetric left-right symmetry originates in the O-world at the seesaw scale M_R [68–70]:

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X \times U(1)_Z,$$

and, correspondingly, in the M-world at the mirror seesaw scale $M'_R = M_R$:

$$SU(3)'_C \times SU(2)'_L \times SU(2)'_R \times U(1)'_X \times U(1)'_Z.$$

The following evolutions appear at the seesaw scale $M_R^{(\prime)}$ and take place for $\mu \geq M_R^{(\prime)}$:

$$\alpha_X^{(\prime)-1}(t_r^{(\prime)}) = \alpha_X^{(\prime)-1}(M_R^{(\prime)}) - \frac{33}{10\pi} t_r^{(\prime)}, \quad (47)$$

$$\alpha_Z^{(\prime)-1}(t_r^{(\prime)}) = \alpha_Z^{(\prime)-1}(M_R^{(\prime)}) - \frac{33}{10\pi} t_r^{(\prime)}, \quad (48)$$

$$\alpha_{22}^{(\prime)-1}(t_r^{(\prime)}) = \alpha_{22}^{(\prime)-1}(M_R^{(\prime)}) - \frac{1}{\pi} t_r^{(\prime)}, \quad (49)$$

with

$$t_r = \ln \left(\frac{\mu}{M_R} \right) \quad \text{and} \quad t'_r = \ln \left(\frac{\mu}{M'_R} \right). \quad (50)$$

4.5 $SU(3)_C \times SU(3)_L$, $SU(3)_C \times SU(3)_L \times SU(3)_R$ and E_6 unification

The intersection of the evolutions (46) and (49) for the O-world couplings gives the scale $M_{GUT} = 3.91 \cdot 10^{15}$ GeV. The evolution of the Abelian group $U(1)_X$:

$$\alpha_X^{-1}(t_r) = \alpha_X^{-1}(M_R) - \frac{33}{10\pi}t_r, \quad (51)$$

which has appeared at the seesaw scale M_R , meets the point M_{GUT} .

Then we have the evolution for $SU(3)_C \times SU(3)_L$ from $M_{GUT} = 3.91 \cdot 10^{15}$ GeV up to the super-GUT scale $M_{SGUT} = 3 \cdot 10^{18}$ GeV :

$$\alpha_{33}^{-1}(t_g) = \alpha_{33}^{-1}(M_{GUT}) + \frac{9}{2\pi}t_g, \quad (52)$$

with the evolution parameter

$$t_g = \ln \left(\frac{\mu}{M_{GUT}} \right).$$

Here M_{SGUT} is the scale of the $SU(3)_C \times SU(3)_L \times SU(3)_R$ -unification.

In our model, from $M_{SGUT} = 3 \cdot 10^{18}$ GeV up to $M_{E_6} = 5 \cdot 10^{18}$ GeV we have the evolution for $SU(3)_C \times SU(3)_L \times SU(3)_R$:

$$\alpha_{333}^{-1}(t_{sg}) = \alpha_{333}^{-1}(M_{SGUT}) + \frac{21}{2\pi}t_{sg}, \quad (53)$$

with

$$t_{sg} = \ln \left(\frac{\mu}{M_{SGUT}} \right).$$

From $M_{SGUT} = 3 \cdot 10^{18}$ GeV down to $M_R = 10^{12}$ GeV we have the evolution of the Abelian $U(1)_Z$ -group:

$$\alpha_Z^{-1}(t_r) = \alpha_Z^{-1}(M_R) - \frac{33}{10\pi}t_r, \quad (54)$$

and down to M_{GUT} – the evolution of the non-asymptotically free supersymmetric $SU(2)_R$ -group:

$$\alpha_{2R}^{-1}(t_r) = \alpha_{2R}^{-1}(M_R) - \frac{1}{2\pi}t_r, \quad (55)$$

with t_r given by Eq. (50).

4.6 Mirror symmetries $SU(3)'_C \times SU(3)'_L$ and $SU(3)'_C \times SU(3)'_L \times SU(3)'_R$

The intersection of the evolutions (46) and (49) for the M-world couplings leads to the scale $M'_{GUT} = 2.46 \cdot 10^{16}$ GeV. The evolution (47) of $\alpha_X'^{-1}(t'_r)$ which begins its running from the seesaw scale M'_R , has its end at the point M'_{GUT} . Then we have the evolution for $SU(3)'_C \times SU(3)'_L$ from $M'_{GUT} = 2.46 \cdot 10^{16}$ GeV up to $M'_{SGUT} = 10^{17}$ GeV (which is arbitrarily chosen, because it is not given by the theory):

$$\alpha'_{33}{}^{-1}(t'_g) = \alpha'_{33}{}^{-1}(M'_{GUT}) + \frac{9}{2\pi}t'_g, \quad (56)$$

with

$$t'_g = \ln \left(\frac{\mu}{M'_{GUT}} \right).$$

From $M'_{SGUT} = 10^{17}$ GeV up to $M_{E_6} = M'_{E_6} = 5 \cdot 10^{18}$ GeV we have the evolution:

$$\alpha'^{-1}_{333}(t'_{sg}) = \alpha'^{-1}_{333}(M'_{SGUT}) + \frac{21}{2\pi} t'_{sg} \quad (57)$$

with the evolution parameter

$$t'_{sg} = \ln \left(\frac{\mu}{M'_{SGUT}} \right).$$

From $M'_{SGUT} = 10^{17}$ GeV down to $M'_R = 10^{12}$ GeV we have the evolutions:

$$\alpha'^{-1}_Z(t'_r) = \alpha'^{-1}_Z(M'_R) - \frac{33}{10\pi} t'_r, \quad (58)$$

$$\alpha'^{-1}_{2R}(t'_r) = \alpha'^{-1}_{2R}(M'_R) - \frac{1}{2\pi} t'_r. \quad (59)$$

The total picture of the evolutions in the O- and M-worlds is presented simultaneously in Fig. 1 for the case:

$$M_{SUSY} = 10 \text{ TeV},$$

$$M_R = 10^{12} \text{ GeV},$$

which give:

$$M_{GUT} = 3.91 \cdot 10^{15} \text{ GeV}.$$

The value of the super-GUT scale in the O-world,

$$M_{SGUT} = 3 \cdot 10^{18} \text{ GeV}$$

depends of the choice of M'_{SGUT} .

We have chosen:

$$\zeta = 10.$$

It is obvious that in this case

$$M'_{SUSY} = 100 \text{ TeV}.$$

$$M'_R = 10^{12} \text{ GeV},$$

which give:

$$M'_{GUT} = 2.46 \cdot 10^{16} \text{ GeV}.$$

Here

$$M'_{SGUT} = 10^{17} \text{ GeV}$$

is arbitrarily chosen and gives:

$$\alpha'^{-1}_{SGUT'} = 28.88. \quad (60)$$

Finally, we obtain the E_6 unification at the scale

$$M'_{E_6} = M_{E_6} = 5 \cdot 10^{18} \text{ GeV},$$

where the inverse coupling constant attains the value

$$\alpha'^{-1}_{E_6} = \alpha^{-1}_{E_6} = 40.82. \quad (61)$$

Fig. 1 visually demonstrates the possibility of the E_6 unification in our model, with the breaking scheme $E_6 \rightarrow SU(3)^3$ in both O- and M- worlds.

5 Cosmological constant in the model of shadow theta-particles

In the previous section we have presented an example of the gauge coupling constant evolutions from the SM up to the E_6 unification scale in the ordinary and mirror worlds with broken mirror parity. We have assumed that the E_6 group of symmetry (inspired by superstring theory) undergoes the breaking: $E_6 \rightarrow SU(3)_C \times SU(3)_L \times SU(3)_R$ in both worlds (O and M) and gives the SM group of symmetry at lower energies. Of course, such a Universe could exist, but it is difficult to find a simple explanation why the observable CC has such a tiny value (2), since, as we have discussed in Subsection 4.2, the considered model with mirror world does not have an extremely large radius of confinement of any gauge interaction. Thus, it is impossible to conceive a vacuum with extremely small vacuum energy density.

5.1 Theta-particles

In Refs. [36,37], Okun developed a theory of θ -particles assuming that in Nature there exists the symmetry group (6):

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times SU(2)_\theta,$$

which contains a non-Abelian $SU(2)_\theta$ group with massless gauge particles, “thetons”, having a macroscopic confinement radius $1/\Lambda_\theta$. Later, in Ref. [71], it was assumed that if any $SU(2)$ group with the scale $\Lambda_2 \sim 10^{-3}$ eV exists, then it is possible to explain the small value (2) of the observable CC . The latter idea was taken up in Refs. [16–21].

In the present context we can obtain the group of symmetry (6) in the shadow world, but not in the ordinary world, as a natural consequence of different schemes of the E_6 -breaking in the O- and Sh-worlds. θ -particles are absent in the ordinary world, because their existence is in disagreement with all experiments. However, they can exist in the shadow world. By analogy with the theory developed in [36,37], we consider shadow thetons $\Theta^i_{\mu\nu}$, $i = 1, 2, 3$, which belong to the adjoint representation of the group $SU(2)'_\theta$, three generations of shadow theta-quarks q'_θ and shadow leptons l'_θ , and the necessary theta-scalars ϕ'_θ for the corresponding breakings. Shadow thetons have macroscopic confinement radius $1/\Lambda'_\theta$, and we assume that

$$\Lambda'_\theta \sim 10^{-3} \text{ eV}. \quad (62)$$

5.2 Shadow World

Superstring theory has led to the speculation that there may exist another form of matter – “shadow matter” – in the Universe (see [31]), which only interacts with ordinary matter via gravity or gravitational-strength interactions. The concept of Shadow Universe was first introduced by K. Nishijima [1]. Further development of this idea was given in Ref. [30] in connection with neutrino experiments. The shadow world, in contrast to the mirror world, can be described by another group of symmetry (or by a chain of groups of symmetry), which is different from the ordinary world symmetry group.

In our model, we shall adopt for the O-world the breaking

$$E_6 \rightarrow SO(10) \times U(1),$$

while for the Sh-world, given the fact that at low energies we wish to have the extra $SU(2)'_\theta$ group, we shall consider the breaking

$$E'_6 \rightarrow SU(6)' \times SU(2)'.$$

5.3 The breaking $E_6 \rightarrow SO(10) \times U(1)_Z$ in the ordinary world

Let us consider now the evolutions of the inverse coupling constants in the O-world and in the Sh-world, with the values of parameters ζ and ξ fixed to

$$\zeta = 30 \quad \text{and} \quad \xi = 1.5. \quad (63)$$

As in the first part of our work, we again consider the running of all gauge coupling constants in the SM and its extensions which are well described by the one-loop approximation of RGEs. We assume that in the ordinary world, from the SM up to the E_6 unification, there exists the following chain of symmetry groups:

$$\begin{aligned} SU(3)_C \times SU(2)_L \times U(1)_Y &\rightarrow [SU(3)_C \times SU(2)_L \times U(1)_Y]_{SUSY} \\ &\rightarrow SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X \times U(1)_Z \\ &\rightarrow SU(4)_C \times SU(2)_L \times SU(2)_R \times U(1)_Z \\ &\rightarrow SO(10) \times U(1)_Z \rightarrow E_6. \end{aligned} \quad (64)$$

5.3.1 Standard Model and MSSM

Starting with the SM and MSSM in the ordinary world we repeat the results of Subsection 4.2. The running of the inverse coupling constants as functions of $x = \log_{10} \mu$ is presented in Fig. 2 (a,b), using the scales $M_{SUSY} = 10$ TeV and $M_R = 2.5 \cdot 10^{14}$ GeV. In these figures, solid lines correspond to the ordinary world. Fig. 2(b) shows the running of the gauge coupling constants near the scale of the E_6 unification (for $x \geq 15$).

NonSUSY groups: b_i :	$SU(3)_C$ 7	$SU(2)_L$ 19/6	$U(1)_Y$ -41/10	
SUSY groups: b_i^{SUSY} :	$SU(3)_C$ 3	$SU(2)_{L,R}$ -1	$SU(2)_L \times SU(2)_R$ $b_{22} = -2$	$U(1)_Y$ -33/5
	$SU(4)$ $b_4 = 5$	$U(1)_X$ -33/5	$U(1)_Z$ -9	$SO(10)$ $b_{10} = 1$

Table 2: The coefficients b_i in the O-world with the breaking $E_6 \rightarrow SO(10) \times U(1)_Z$.

5.3.2 Left-right symmetry, $SO(10)$ and E_6 unification

We assume that the following supersymmetric left-right symmetry originates at the seesaw scale M_R [68–70] :

$$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X \times U(1)_Z.$$

At the next step, we assume that the group

$$SU(4)_C \times SU(2)_L \times SU(2)_R$$

of the Pati-Salam model [68] originates at the scale M_4 , giving the following extension of the symmetry group :

$$\begin{aligned} &SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_X \times U(1)_Z \\ &\rightarrow SU(4)_C \times SU(2)_L \times SU(2)_R \times U(1)_Z. \end{aligned} \quad (65)$$

At the scale M_{GUT} , the $SO(10)$ -unification occurs:

$$SU(4)_C \times SU(2)_L \times SU(2)_R \rightarrow SO(10). \quad (66)$$

The evolution of $\alpha_{10}^{-1}(\mu)$, corresponding to $SO(10)$, occurs from the scale M_{GUT} up to the super-GUT scale M_{SGUT} of the E_6 unification:

$$SO(10) \times U(1)_Z \rightarrow E_6.$$

The super-GUT scale is ³

$$M_{SGUT} = M_{E_6} \sim 10^{18} \text{GeV}.$$

The coefficients (slopes) b_i , describing the running of the coupling constants with our choice of gauge groups and particle content in the O-world, are given in Table 2 (in accord with Refs. [20, 44, 64, 65]).

5.4 Gauge coupling constant evolutions in the shadow world

5.4.1 Gauge coupling constant evolutions in the shadow SM' and MSSM'

Let us consider now the shadow world and the extension of the SM', for the moment ignoring the extra $SU(2)'$ group which survives at low energies in this scheme of breaking. The first steps of such an extension are:

$$SU(3)'_C \times SU(2)'_L \times U(1)'_Y$$

³A comment on terminology: the scales M_{GUT} and M_{SGUT} in the model with Sh-world have nothing to do with the scales considered in the first part of the work, i.e. in the model with M-world (Section 4).

Nonsupersymmetric groups: b_i :	$SU(3)'_C$ 7	$SU(2)'_L$ 19/6	$SU(2)'_\theta$ 3	$U(1)'_Y$ -41/10
Supersymmetric groups: b_i :	$SU(3)'_C$ 3	$SU(2)'_L$ -1	$SU(2)'_\theta$ -2	$U(1)'_Y$ -33/5
	$SU(4)'_C$ 5	$U(1)'_X$ -33/5	$U(1)'_Z$ -9	$SU'(6)$ 11

Table 3: The coefficients b_i in the Shadow World.

$$\begin{aligned} &\rightarrow [SU(3)'_C \times SU(2)'_L \times U(1)'_Y]_{SUSY} \\ &\rightarrow [SU(3)'_C \times SU(2)'_L \times U(1)'_X \times U(1)'_Z]_{SUSY}, \end{aligned}$$

and then

$$\begin{aligned} &[SU(3)'_C \times SU(2)'_L \times U(1)'_X]_{SUSY} \\ &\rightarrow SU(4)'_C \times SU(2)'_L. \end{aligned}$$

In the SM' -sector of the shadow world we have the following evolutions:

$$\alpha_i'^{-1}(\mu) = \alpha_i'^{-1}(M'_t) + \frac{b_i}{2\pi} t' = \frac{b_i}{2\pi} \ln \frac{\mu}{\Lambda'_i} \quad (67)$$

for $i = 1, 2, 3$, where $M'_t = \zeta M_t$. We should point out that the scales Λ'_i and Λ_i are different, though the slopes are the same:

$$b'_i = b_i.$$

As in the mirror world of the first part of our paper, the supersymmetry breaking scale in the Sh-world is larger: $M'_{SUSY} = \zeta M_{SUSY}$. The shadow MSSM' leads to the evolutions $\alpha_i'^{-1}(\mu)$ (where $i = 1, 2, 3$), which run from the scale M'_{SUSY} up to the scale M'_R in the Sh-world.

At the scale $M'_R = M_R$ the shadow right-handed neutrinos appear and the chain of possible symmetries leading to the E'_6 unification is (see Ref. [20]):

$$\begin{aligned} &[SU(3)'_C \times SU(2)'_L \times U(1)'_Y]_{SUSY} \\ &\rightarrow [SU(3)'_C \times SU(2)'_L \times U(1)'_X \times U(1)'_Z]_{SUSY}, \end{aligned} \quad (68)$$

$$[SU(3)'_C \times SU(2)'_L \times U(1)'_X]_{SUSY} \rightarrow SU(4)'_C \times SU(2)'_L. \quad (69)$$

The coefficients b_i (slopes), describing the evolutions in the shadow world, are given in Table 3 (see Refs. [20, 44, 64, 65]).

5.4.2 Shadow gauge coupling constant evolutions from $SU(6)'$

In the shadow world the evolutions are quite different from the O-world. As a result, at the GUT scale M'_{GUT} we reach $SU(6)'$ -unification, and not $SO(10)'$ -unification:

$$SU(4)'_C \times SU(2)'_L \times U(1)'_Z \rightarrow SU(6)'. \quad (70)$$

Then the $SU(6)'$ evolution occurs in the Sh-world up to the super-GUT-scale

$$M'_{SUT} = M'_{E_6}.$$

In the Sh-world the final chain is:

$$SU(6)' \times SU(2)' \rightarrow E'_6, \quad (71)$$

where the $SU(2)'$ survives unbroken up to the low energies of SM'.

Now we are confronted with the question: what group of symmetry $SU(2)'$, unknown in the O-world, exists in the Sh-world, ensuring the E'_6 unification at the super-GUT-scale $M'_{SGUT} = M'_{E_6} = M_{E_6}$? In this work we assume that this new $SU(2)'$ group is precisely the $SU(2)'_\theta$ gauge group of symmetry suggested in Refs. [36, 37].

The unification $E_6 = E'_6$ occurs at the scale :

$$M'_{SGUT} = M'_{E_6} = M_{SGUT} = M_{E_6} \simeq 10^{18} \text{ GeV} \quad (72)$$

and restores the mirror parity MP.

Finally, we obtain the following chain of symmetry breakings in the shadow world:

$$\begin{aligned} E'_6 &\rightarrow SU(6)' \times SU(2)'_\theta \rightarrow SU(4)'_C \times SU(2)'_L \times SU(2)'_\theta \times U(1)'_Z \\ &\rightarrow SU(3)'_C \times SU(2)'_L \times SU(2)'_\theta \times U(1)'_X \times U(1)'_Z \\ &\rightarrow SU(3)'_C \times SU(2)'_L \times SU(2)'_\theta \times U(1)'_Y. \end{aligned} \quad (73)$$

5.5 New shadow gauge group $SU(2)'_\theta$

The reason for our choice of the $SU(2)'_\theta$ group was to obtain the evolution $\alpha'^{-1}_{2\theta}(\mu)$, which leads to the new scale (62) in the shadow world at extremely low energies, according to the ideas considered in Refs. [16–21, 36, 37].

By comparison with the content of the 27-plet of E_6 having 16 fermions (see Eqs. (9-11)), we should consider theta-quarks as θ –doublets and shadow leptons as θ –singlets. Then we have 12+4 fermions, with 12 quarks having $3 \times 2 \times 2$ degrees of freedom, corresponding to $SU(3)_C \times SU(2)_L \times SU(2)_\theta$. The scalars ϕ'_θ also can be considered as doublets of $SU(2)'_\theta$. Theta-quarks can be heavier than ordinary quarks, having additional interactions with thetons.

We start at high energies $\mu > M'_t$ with three generations of theta-quarks and assume the existence of two doublets of scalar fields ϕ'_θ with $\langle \phi'_\theta \rangle \sim 10^{-3}$ eV. Then we have the following slopes given by Refs. [20], [44] (see also [64] and [65]):

$$b_{2\theta} = 3 \quad \text{and} \quad b_{2\theta}^{\text{SUSY}} = -2. \quad (74)$$

Of course, near the scale Λ'_θ only theta-quarks of the first generation contribute, and it is easy to obtain the value $\Lambda'_\theta \approx 3 \cdot 10^{-3}$ eV. Theta-quarks of the first generation are stable, due to the conservation of theta-charge [36, 37].

We also consider a complex scalar field

$$\varphi_\theta = (1, 1, 0, 1),$$

which is a singlet under the symmetry group

$$G' = SU(3)'_C \times SU(2)'_L \times U(1)'_Y \times SU(2)'_\theta.$$

This comes from 27-plet of the E'_6 unification (see Eq. (14)).

In Figs. 3 (a,b) we have shown the evolutions of all $\alpha'^{-1}(\mu)$ in the Sh-world, given by dashed lines, together with $\alpha'_{2\theta}^{-1}(\mu)$.

The comparison of the evolutions in the O- and Sh-worlds is presented in Figs. 4 (a,b).

The parameters of our model are as follows:

$$M_{SUSY} = 10 \text{ TeV},$$

$$\zeta = 30.$$

In this case we have:

$$M'_{SUSY} = 300 \text{ TeV},$$

and

$$M_R = M'_R = 2.5 \cdot 10^{14} \text{ GeV}.$$

Here

$$M_4 = 9.40 \cdot 10^{15} \text{ GeV},$$

$$M'_4 = 3.01 \cdot 10^{17} \text{ GeV},$$

$$M_{GUT} = 1.10 \cdot 10^{16} \text{ GeV},$$

$$M'_{GUT} = 6.37 \cdot 10^{17} \text{ GeV},$$

$$M_{SGUT} = M'_{SGUT} = M_{E_6} = 6.98 \cdot 10^{17} \text{ GeV},$$

and

$$\alpha_{E_6}^{-1} = 27.64. \tag{75}$$

6 Cosmological Constant, Dark Energy and Dark Matter

From the point of view of particle physics the cosmological constant naturally arises as energy density of the vacuum.

For the present epoch, the Hubble parameter H is given by the following value:

$$H = 1.5 \times 10^{-42} \text{ GeV}, \tag{76}$$

and the critical density of the Universe is

$$\rho_c = 3H^2/8\pi G = (2.5 \times 10^{-12} \text{ GeV})^4. \tag{77}$$

According to the Particle Data Group [67], the fraction of the dark energy corresponds to

$$\rho_{DE} \approx 0.75 \rho_c \approx (2.3 \times 10^{-3} \text{ eV})^4. \tag{78}$$

The Λ CDM cosmological model predicts that the cosmological constant Λ is equal to

$$CC = \Lambda = \rho_{vac} = \rho_{DE}.$$

Given by Eq.(78), CC is extremely small. This is a result of recent cosmological observations (see, for example, Refs. [72–74]).

Modern Quantum Field Theory (QFT) gives an energy scale of Λ much larger than the present cosmological value. This is the cosmological constant problem [75] and was well known to exist long before the discovery of the accelerated expansion of the Universe in 1998.

There have been a number of attempts to solve this problem.

Previously in Ref. [76] and also in Ref. [77, 78] it was shown that SUGRA models which ensure the vanishing of the vacuum energy density near the physical vacuum lead to a natural realization of the Multiple Point Model (MPP) [79–81] (see also the reviews [82, 83]) describing the degenerate vacua with naturally tiny CC .

In the present paper it is assumed that all contributions to CC are canceled, except the condensates (zero mode contributions) of shadow θ particles, especially thetons. Their contributions provide the minimum of the overall effective potential:

$$\min V_{eff} = \rho_{DE} = \rho_{vac} \simeq \Lambda_\theta'^4 \simeq (2.3 \times 10^{-3} \text{ eV})^4. \quad (79)$$

It is essential that in the low energy region we have the G_{SM} symmetry group in the O-world, but the $G'_{SM'} \times SU(2)'_\theta$ group of symmetry in the Sh-world. If we assume that superstring theory, or supergravity provides the cancellation of the SM and SM' contributions to CC , then we can relate the value (79) with the result of confinement given by $SU(2)'_\theta$. This phenomenon is not obvious, but it is possible to fix the existence of the group of symmetry $SU(2)'_\theta$ as a consequence of the E_6 -breakdown in the Sh-world, using (modern and future) astrophysical measurements. We have obtained E_6 unification in the 4-dimensional space considering the spontaneous compactification of the ten-dimensional $E_8 \times E'_8$ superstring theory. The breakdown of compactification could be important in solving the cosmological problem (see for example [84–86]). We hope to investigate this problem in forthcoming communications.

There exists an axial $U(1)_A$ global symmetry in our theory with a current having $SU(2)'_\theta$ anomaly, which is spontaneously broken at the scale f_θ by a singlet complex scalar field φ_θ , with a VEV $\langle \varphi \rangle = f_\theta$, i.e.

$$\varphi = (f_\theta + \sigma) \exp(ia_\theta/f_\theta). \quad (80)$$

The boson a_θ (imaginary part of the singlet scalar field φ_θ) is an axion and could be identified with a massless Nambu-Goldstone (NG) boson if the $U(1)_A$ symmetry is not spontaneously broken. However, the spontaneous breaking of the global $U(1)_A$ by $SU(2)'_\theta$ instantons inverts a_θ into a pseudo Nambu-Goldstone (PNG) boson.

The singlet complex scalar field φ_θ reproduces a Peccei-Quinn (PQ) model [87] (well known in QCD, but having a different meaning in our model). In the shadow world with shadow θ -particles the vacuum energy density is given by Eq. (79), which means that

$$\Lambda_\theta' \approx 2.3 \times 10^{-3} \text{ eV}. \quad (81)$$

Near the vacuum, a PNG mode a_θ emerges the following PQ axion potential:

$$V_{PQ}(a_\theta) \approx (\Lambda_\theta')^4 (1 - \cos(a_\theta/f_\theta)). \quad (82)$$

This axion potential exhibits minima at

$$\cos(a_\theta/f_\theta) = 1, \quad (83)$$

i.e.

$$(a_\theta)_{min} = a_n = 2\pi n f_\theta, \quad n = 0, 1, \dots \quad (84)$$

For small fields a_θ we expand the effective potential near the minimum:

$$V_{eff} \approx (\Lambda'_\theta)^4 (1 + \frac{1}{2}(a_\theta/f_\theta)^2 + \dots) = (\Lambda'_\theta)^4 + \frac{1}{2}m^2 a_\theta^2 + \dots, \quad (85)$$

and hence the PNG axion mass squared is given by:

$$m^2 \sim \Lambda'^4_\theta / f_\theta^2. \quad (86)$$

Let us assume that at the cosmological epoch when $U(1)_A$ was spontaneously broken, the value of the axion field a_θ was deviated from zero, and it was $a_{\theta,in} \sim f_\theta$. The value of the scale $f_\theta \sim 10^{18}$ GeV (near the E_6 unification breaking scale) makes it natural that the $U(1)_A$ symmetry was broken before inflation, and the initial value $a_{\theta,in}$ was inflated above the present horizon. So after the inflation breaking scale, and in particular in the present Universe, the field a_θ is spatially homogeneous (constant), and the initial energy density corresponding to $a_{\theta,in}$ is also spatially homogeneous:

$$\rho_{in} = V(a_{\theta,in}) \simeq \Lambda'^4_\theta (1 - \cos(a_{\theta,in}/f_\theta)), \quad (87)$$

and its value changes only with time.

For the expanding Universe the equation of motion (EOM) of the classical field a_θ is:

$$\frac{d^2 a_\theta}{dt^2} + 3H \frac{da_\theta}{dt} + V'(a_\theta) = 0, \quad (88)$$

where H is the Hubble parameter (76).

For small a_θ we have:

$$V'(a_\theta) = m^2 a_\theta. \quad (89)$$

If $\Lambda'_\theta \sim 10^{-3}$ eV and $f_\theta \sim 10^{18}$ GeV, then from Eq. (86) we obtain the value of the axion mass:

$$m \sim \Lambda'^2_\theta / f_\theta \sim 10^{-42} \text{ GeV}. \quad (90)$$

Now, it is natural to assume that the initial velocity $\dot{a}_{\theta,in}$ was small:

$$\dot{a}_{\theta,in} \sim H f_\theta. \quad (91)$$

Then, for $3H^2 \gg m^2$ the potential curvature $V'(a_\theta)$ in the above EOM can be neglected, and we have a solution with a_θ remaining the constant in time.

Now, having $m^2 < 3H^2$, we see that the classical PNG field a_θ does not start the oscillation and in the present epoch its energy density remains constant (does not scale with time). In this case, for the present epoch, the energy of the PNG field a_θ can imitate dark energy, providing the equation of state $\rho = wp$ with $w \approx -1$, but not exactly equal to -1 (quintessence model). Of course, to claim that this can explain the present amount of dark energy, one again must assume that the major constant contributions to the cosmological term are canceled by some means, i.e. the true cosmological constant is almost zero due to some (yet unknown) symmetry (see for example [78]), or due to dynamical reasons. Also the gravity itself can be modified so that it does not feel the truly constant terms in the energy (see for example Ref. [88]). In this case one

can ascribe the present acceleration of the Universe to such a PNG quintessence field, with the implication that the acceleration will not be forever, but it will finish as soon as $m^2 \sim 3H^2$ will be achieved. After that the PQ classical energy will behave as a dark matter component and not as dark energy.

In the present paper we have suggested a model in which our Universe was trapped in the vacuum (79) and exists there at the present time with a tiny cosmological constant CC :

$$CC = (\Lambda'_\theta)^4 \approx (2.3 \times 10^{-3} \text{ eV})^4. \quad (92)$$

Such properties of the present axion lead to the ‘ Λ CDM’ model of our accelerating expanding Universe [7–11]. By this reason, the axion a_θ could be called an ‘acceleron’, and the field σ given by Eq. (80) is an inflaton.

6.1 Dark matter

The existence of dark matter in the Universe, which is non-luminous and non-absorbing matter, is now well established in astrophysics. Recently very interesting investigations of DM were presented in Refs. [89–95].

For the ratios of densities,

$$\Omega_X = \rho_x / \rho_c, \quad (93)$$

where ρ_c is the critical energy density, cosmological measurements give the following density ratios of the total Universe [67]:

$$\Omega_0 = \Omega_r + \Omega_M + \Omega_\Lambda = 1, \quad (94)$$

where Ω_r is a relativistic (radiation) density ratio and

$$\Omega_\Lambda = \Omega_{DE} \sim 75\%,$$

for the mysterious Dark Energy, which is responsible for the acceleration of the Universe, while

$$\Omega_M \approx \Omega_B + \Omega_{DM} \sim 25\%, \quad (95)$$

with

$$\Omega_B \approx 4\%$$

for (visible) baryons and

$$\Omega_{DM} \approx 21\%$$

for the Dark Matter.

Here we propose that a plausible candidate for DM is a shadow world with its shadow quarks, leptons, bosons and super-partners, of which the shadow baryons are dominant:

$$\Omega_{DM} \approx \Omega_{B'}.$$

We see that

$$\Omega_{B'} \approx 5\Omega_B,$$

meaning that the shadow baryon density is larger than the ordinary one.

The new gauge group $SU(2)'_\theta$ gives the running of $(\alpha')_{2\theta}^{-1}(\mu)$. Near the scale $\Lambda'_\theta \sim 10^{-3}$ eV, the coupling constant $g'_{2\theta}$ grows infinitely. But at higher energies (see Figs. 3 and 4) this coupling constant is comparable with the electromagnetic one. Here we would like to emphasize that the shadow quarks q'_θ of the first generation are stable, and can participate in the formation of shadow “hadrons”, which can be considered as good candidates for the Cold Dark Matter (CDM). So we have two types of shadow baryons: baryons b' constructed from shadow quarks q' which are singlets of $SU(2)'_\theta$, and baryons b'_θ constructed from the quark q' and two shadow θ -quarks q'_θ , in order to preserve θ -charge conservation. Then,

$$\Omega_{B'} = \Omega_{b'+b'_\theta} \approx 5\Omega_B.$$

We shall study in detail the DM in a forthcoming communication.

7 Conclusions

We have considered cosmological implications of the parallel ordinary and mirror or shadow worlds, with broken mirror parity. The parameter characterizing the breaking of MP is $\zeta = v'/v$, where v' and v are the VEVs of the Higgs bosons in the M (or Sh)- and O-worlds, respectively.

We have assumed that at very high energies there exists the E_6 unification predicted by superstring theory, which restores the broken mirror parity MP at the scale $\sim 10^{18}$ GeV. We have chosen a model which leads to asymptotically free E_6 unification, what is not always fulfilled.

In the first part of this paper, we have considered E_6 unification in the O- and M-worlds with the breaking $E_6 \rightarrow SU(3)_C \times SU(3)_L \times SU(3)_R$. The model of unification is very simple, but the unification is non-trivial. This breaking scheme is the only one which enables us to obtain the E_6 unification of the O- and M- worlds below the Planck scale and with plausible values for the SUSY and seesaw scales. The other two possible breaking schemes of E_6 in the O- and M- world, with broken MP, would not lead to unification.

Aiming at explaining the tiny value of the cosmological constant CC , we have assumed the existence of a shadow (not mirror) world parallel to our ordinary world. For numerical calculations, we have used the value $\zeta = 30$. The comparison of the coupling constants evolutions in the O- and Sh-worlds is given in Figs. 4 (a,b). The breaking of the unification E'_6 in the shadow world is based on the group $E'_6 \rightarrow SU(6)' \times SU(2)'_\theta$. The $SU(2)'_\theta$ part of our model follows the theory of Okun [36,37] for theta-particles.

The existence of the new gauge group $SU(2)'_\theta$ in the Sh-world gives significant consequences for cosmology: it explains the tiny value of CC and the Λ CDM model of our accelerating Universe. It was shown in Subsection 6.1 that the existence of the scale $\Lambda'_\theta \sim 10^{-3}$ eV explains the value of cosmological constant, $CC \approx (2.3 \times 10^{-3} \text{ eV})^4$, which is given by recent astrophysical measurements. The bound states – shadow “hadrons”, the result of confinement of shadow quarks q' and q'_θ – are candidates for the Cold Dark Matter (CDM).

It should be emphasized that the present work opens the possibility to study in detail the DM, and specify a grand unification group, such as E_6 , from Cosmology.

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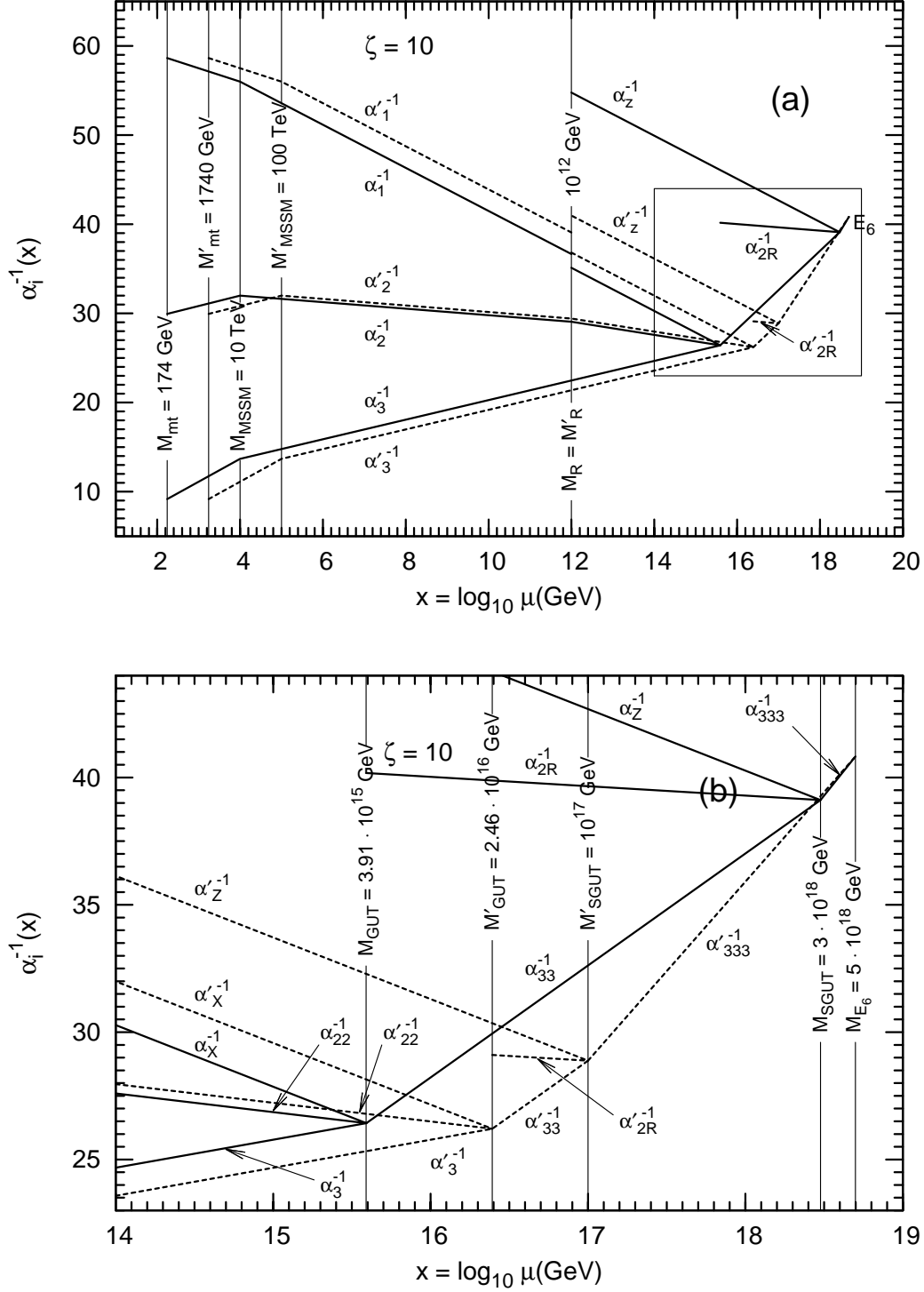


Fig. 1: The running of the inverse coupling constants $\alpha_i^{-1}(x)$ in both ordinary and mirror worlds with broken mirror parity, from the Standard Model up to the E_6 unification, for SUSY breaking scales $M_{\text{SUSY}} = 10 \text{ TeV}$, $M'_{\text{SUSY}} = 100 \text{ TeV}$ and seesaw scales $M_R = M'_R = 10^{12} \text{ GeV}$; $\zeta = 10$. This case gives: $M_{\text{SGUT}} = 3 \cdot 10^{18} \text{ GeV}$, $M'_{\text{SGUT}} = 10^{17} \text{ GeV}$, $M_{E_6} = 5 \cdot 10^{18} \text{ GeV}$ and $\alpha_{E_6}^{-1} = 40.82$. Solid lines correspond to the ordinary world, while dashed lines correspond to the mirror world.

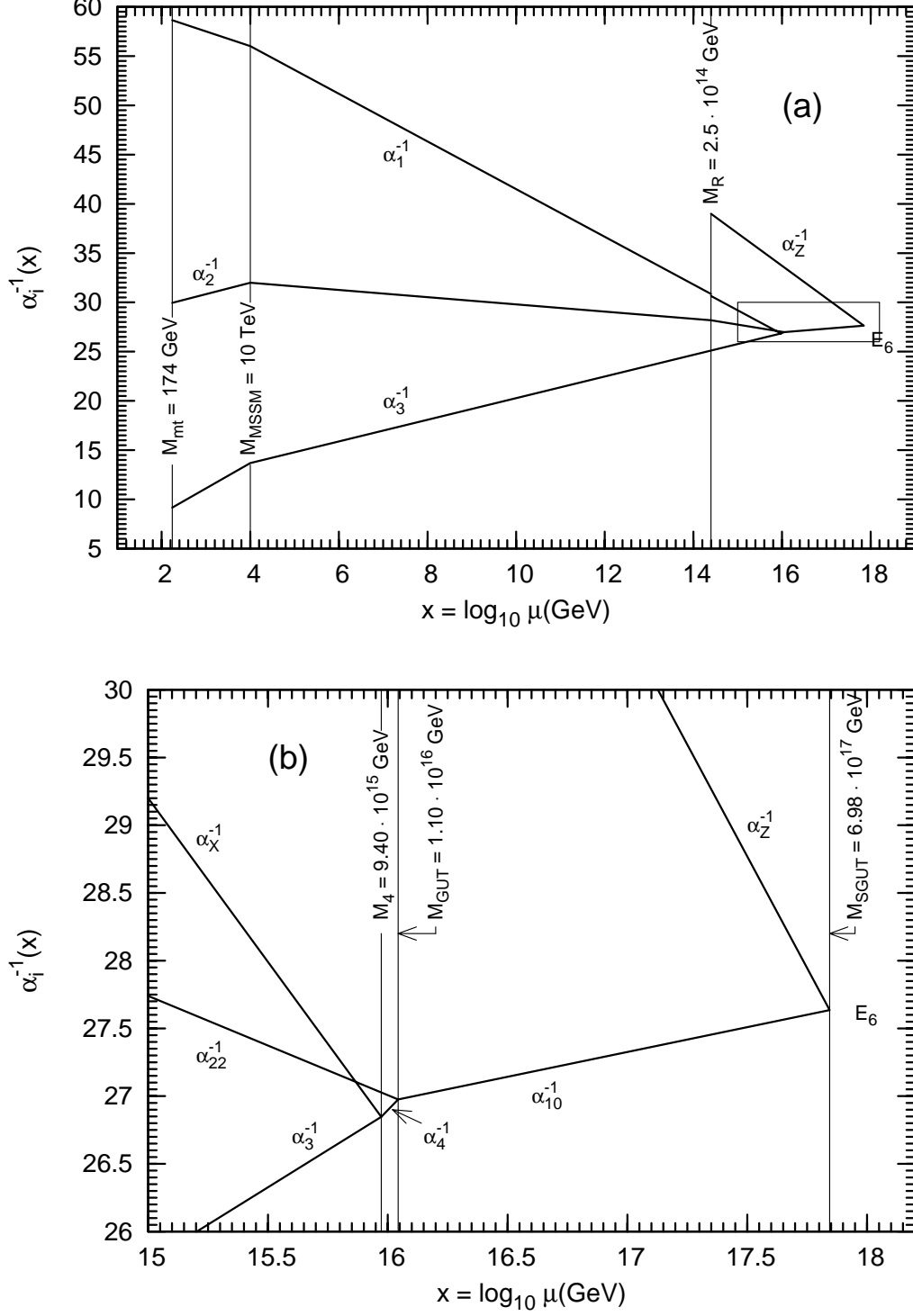


Fig. 2: Figure (a) presents the running of the inverse coupling constants $\alpha_i^{-1}(x)$ in the ordinary world, from the Standard Model up to the E_6 unification for SUSY breaking scale $M_{\text{SUSY}} = 10 \text{ TeV}$ and seesaw scale $M_R = 2.5 \cdot 10^{14} \text{ GeV}$. This case gives: $M_{\text{SGUT}} = M_{E_6} = 6.98 \cdot 10^{17} \text{ GeV}$ and $\alpha_{E_6}^{-1} = 27.64$. Figure (b) is the same as (a), but zoomed in the scale region from 10^{15} GeV up to the E_6 unification to show the details.

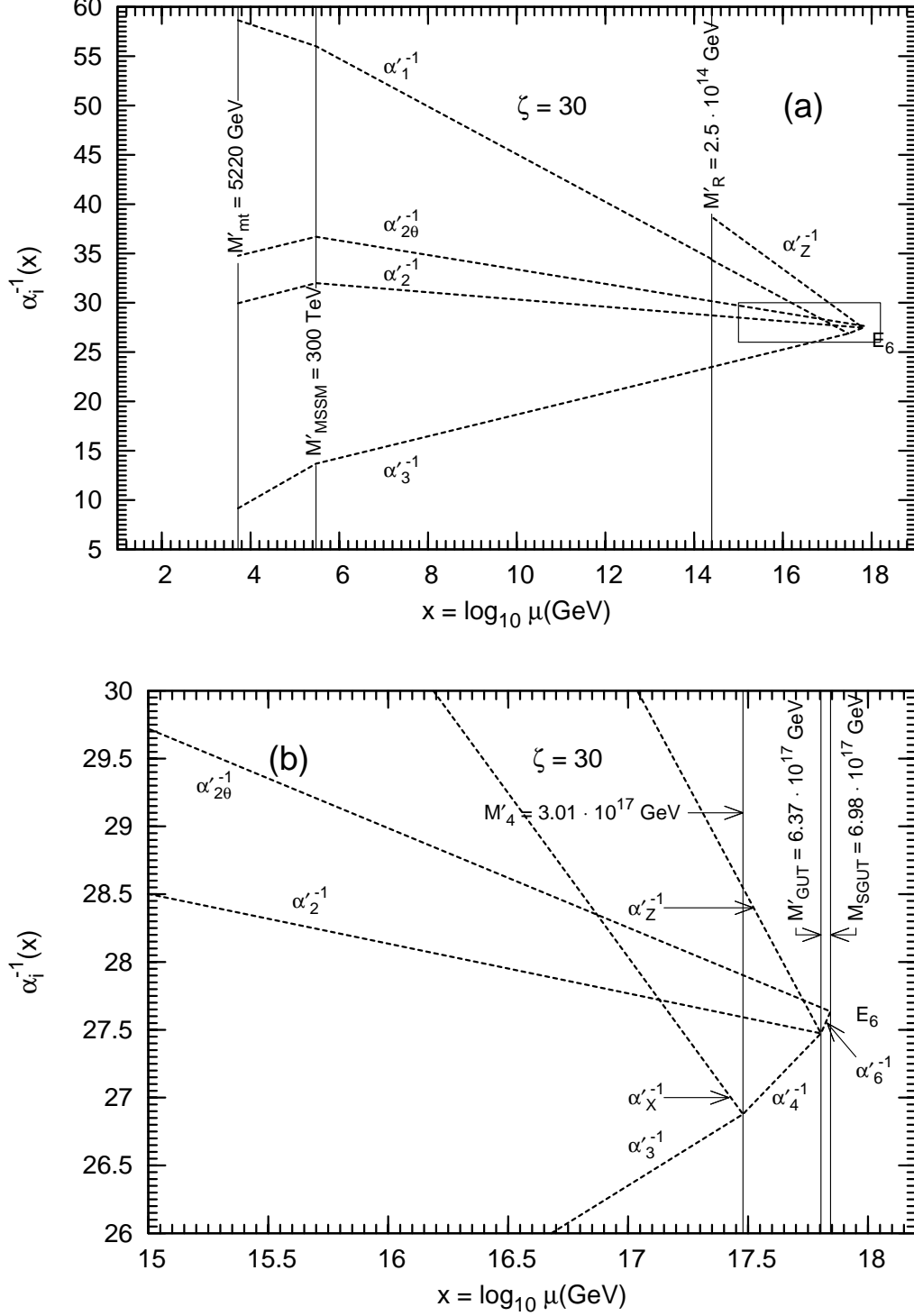


Fig. 3: Figure (a) presents the running of the inverse coupling constants $\alpha_i^{-1}(x)$ in the mirror world from the Standard Model up to the E_6 unification for mirror SUSY breaking scale $M'_{\text{SUSY}} = 300 \text{ TeV}$ and mirror seesaw scale $M'_R = 2.5 \cdot 10^{14} \text{ GeV}$; $\zeta = 30$. This case gives: $M'_{\text{SGUT}} = M_{E_6} = 6.98 \cdot 10^{17} \text{ GeV}$ and $\alpha_{E_6}^{-1} = 27.64$. Figure (b) is the same as (a), but zoomed in the scale region from 10^{15} GeV up to the E_6 unification to show the details.

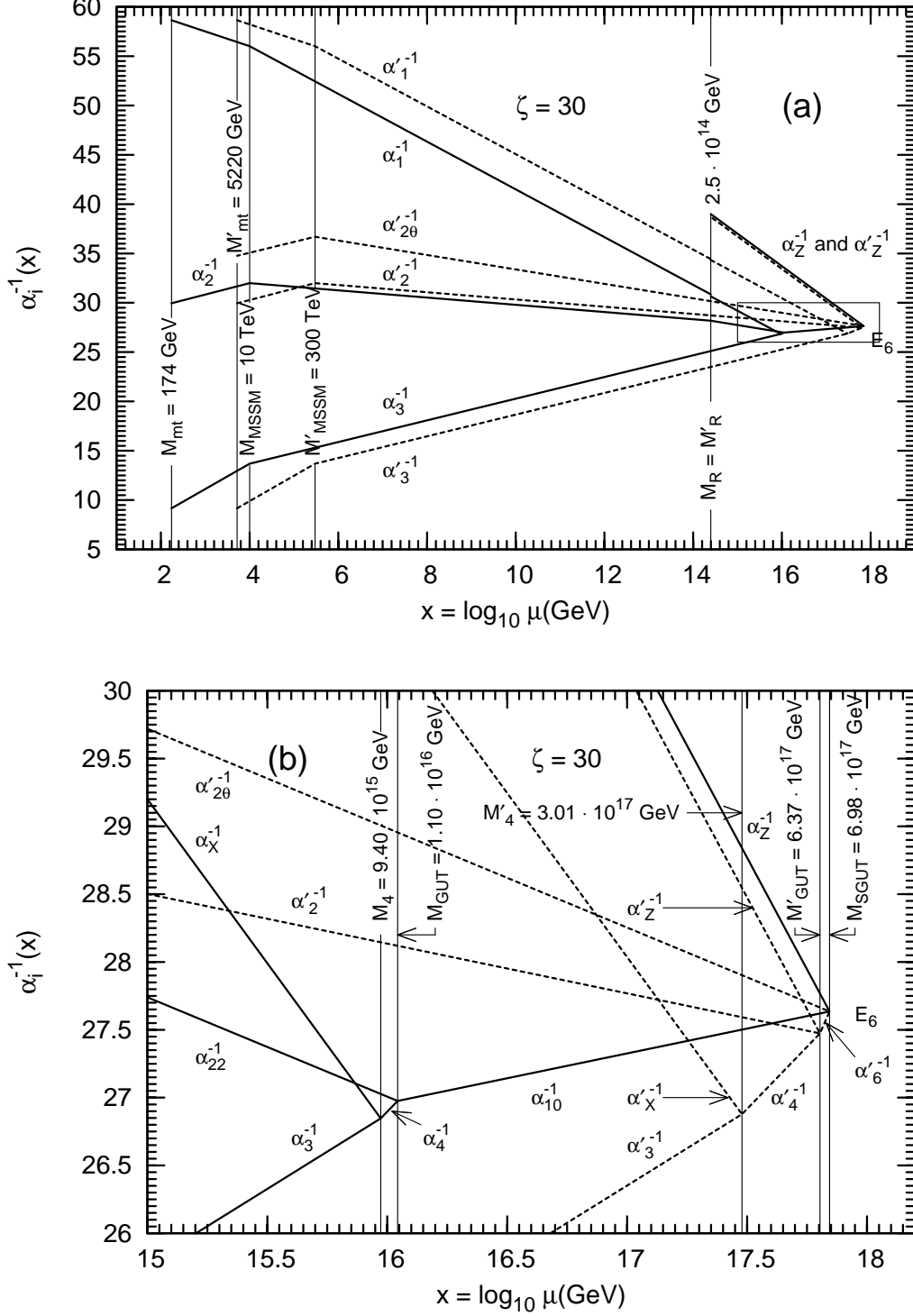


Fig. 4: Figure (a) shows the running of the inverse coupling constants $\alpha_i^{-1}(x)$ in both ordinary and mirror worlds with broken mirror parity, from the Standard Model up to the E_6 unification for SUSY breaking scales $M_{\text{SUSY}} = 10 \text{ TeV}$, $M'_{\text{SUSY}} = 300 \text{ TeV}$ and seesaw scales $M_R = M'_R = 2.5 \cdot 10^{14} \text{ GeV}$; $\zeta = 30$. This case gives: $M_{\text{SGUT}} = M'_{\text{SGUT}} = M_{E_6} = 6.98 \cdot 10^{17} \text{ GeV}$ and $\alpha_{E_6}^{-1} = 27.64$. Figure (b) is the same as (a), but zoomed in the scale region from 10^{15} GeV up to the E_6 unification to show the details.